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Behind-the-Meter Storage Overview

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Project ID # **bat442**

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Overview

Timeline

- October 1st 2018 - September 30th 2025.
- Percent complete: 40%

Barriers

- Development of stationary storage systems to enable extreme fast charging of EVs and energy efficient grid interactive buildings
  - Cost, Performance and Safety

Budget

- Funding for FY 20: $2500K

Partners

- A joint project between VTO, BTO and SETO.
- Four Laboratory Team lead by NREL:
  - Sandia National Laboratory
  - Argonne National Laboratory
  - Idaho National Laboratory

BTMS: Milestones VTO

Q1: Presentation to Technical Review committee and provided feedback from the meeting to EERE. (**complete**)

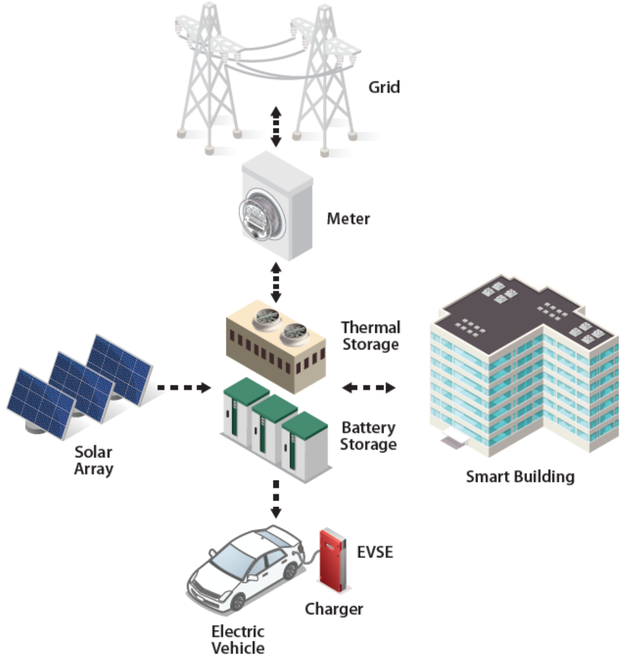
Q2: Establish initial protocols and procedures for BTMS electrochemical energy cell evaluation that will enable feed back to the cost analysis task and the machine-learning physic-based model development tasks. (**complete**)

Q3: Go-No go on graphite anodes related to the BTMS EES cost and lifetime targets. Go will be determined by experimental evidence that graphite-based cells have demonstrated 1000 cycles and the lifetime model predict can achieve at least 5000 cycles (50% of target) and have projected cost targets of $250/WKh, usable energy (2.5 x target).

Q3: Determine thickness vs temperature limitations for non-Co electrodes.

Q4: Thick electrode cells under test using BTMS protocols.

Behind-The-Meter Storage (BTMS)
Low TRL Work Guided by System Level Thinking.



- Focus on specific end user outcomes.
- Minimize cost of energy to user.
- Buildings are the largest electrical users.
- EVs will be charged at buildings.
- Demand charges need to be eliminated.
- Grid impacts minimized.
- Integration of PV is/will be common.
- Both electrons and heat need to be stored.
- New batteries are needed.
- New thermal storage are needed.

A partnership with the Vehicles, Buildings, and Solar Offices

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BTMS: Basic Premises

- **Technologically agnostic** in the approach to storage systems (both electrochemical and thermal storage).
- **EV Charging will occur at buildings**.
- All low TRL research will be guided by the system requirements.
- **Non-critical materials will be a foundation**.
- Current targets for vehicles will not lead to batteries that meet long-term storage requirements.
- Thermal storage and management will enable optimizing energy efficiency and minimizing cost in buildings applications.
- **System safety is critical in a building environment.**

- Testing of new materials in full systems will be the metric for success (safety, lifetime, energy density, and cost).
- This project takes advantage of the major investment the **VTO** Battery program has made in infrastructure, capabilities, and materials development coupled with the **BTO's** investments in thermal management and storage.
- Ongoing and integrated cost analysis will be essential to success.

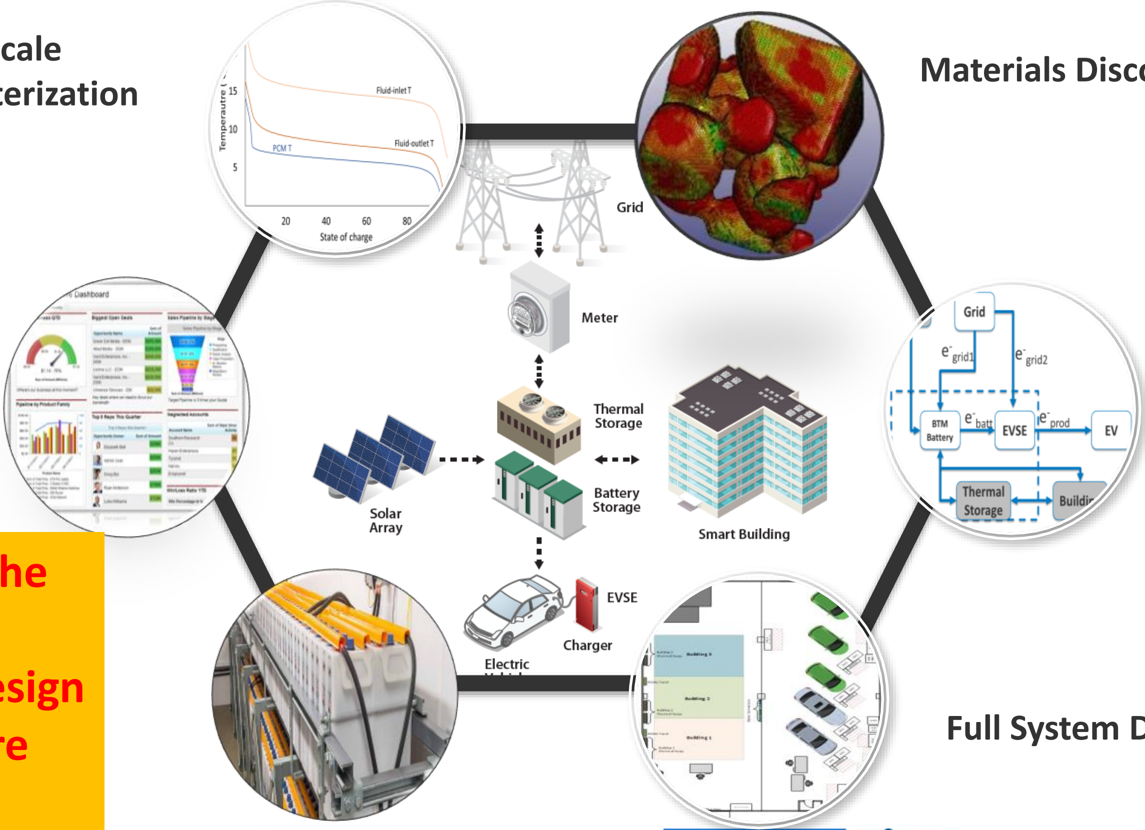
Behind the meter storage (BTMS) a full systems approach

Multi-scale characterization

Materials Discovery

Metrics and target determination

Integrated-system modeling and design



Full System Design

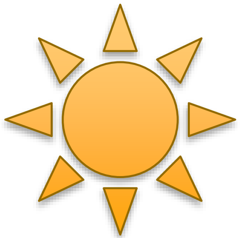
All aspects of the system from materials to design and controls are part of the solution.

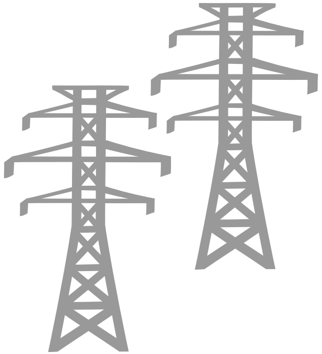
Integration experiments

BTMS: Metrics and target determination
DEFINE THE PROBLEM

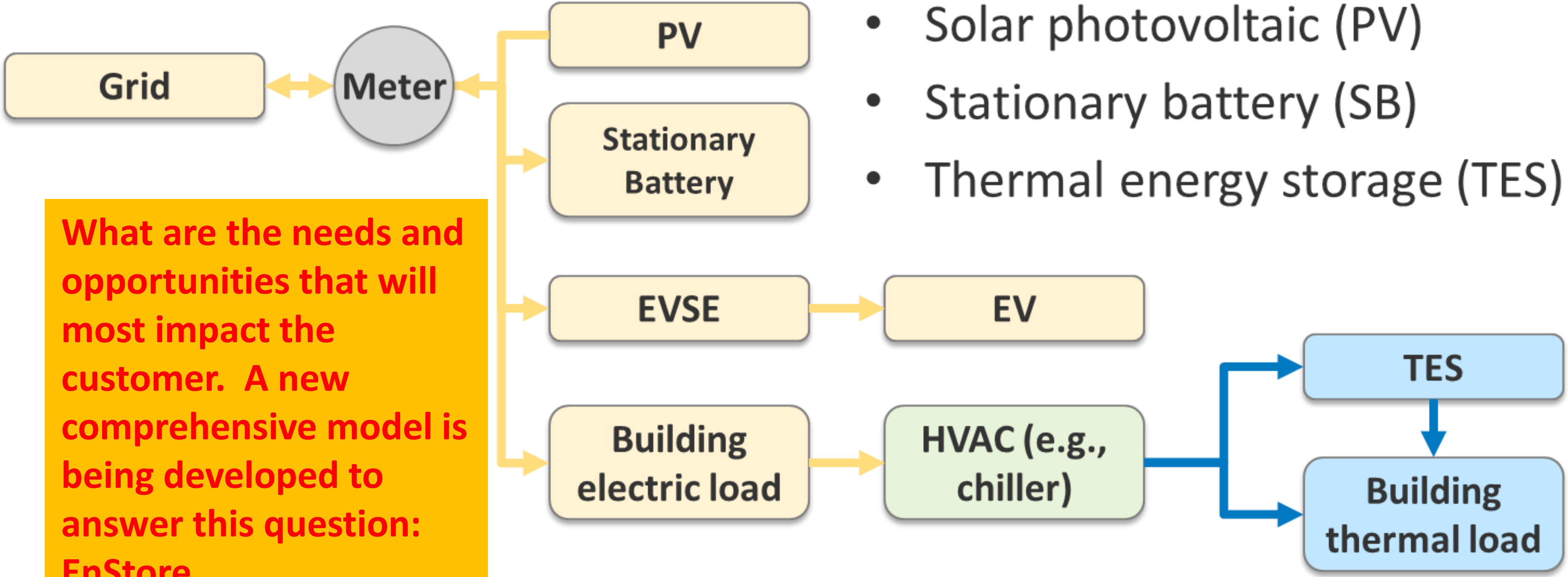
What are the ***optimal*** **system designs** and **energy flows** for **thermal** and **electrochemical** behind-the-meter-storage with on-site **PV** generation enabling **fast EV charging** if we vary

climate, building type, and utility rate structure?





Optimize System Sizing to Minimize Cost: PV + SB + EV + TES



- Solar photovoltaic (PV)
- Stationary battery (SB)
- Thermal energy storage (TES)

What are the needs and opportunities that will most impact the customer. A new comprehensive model is being developed to answer this question: EnStore

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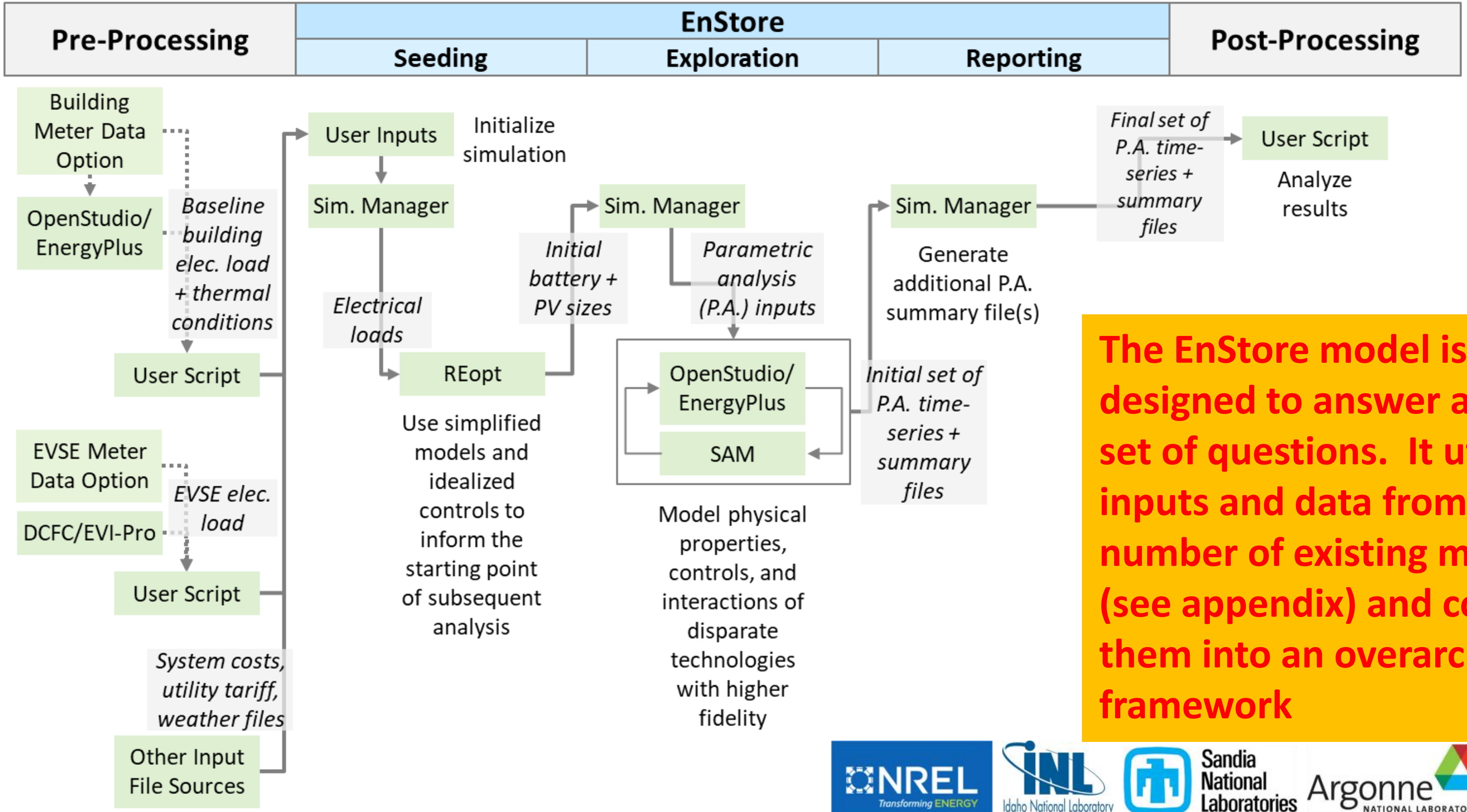
Workflow for EnStore model



The EnStore model is designed to answer a wide set of questions. It utilizes inputs and data from a number of existing models (see appendix) and combines them into an overarching framework

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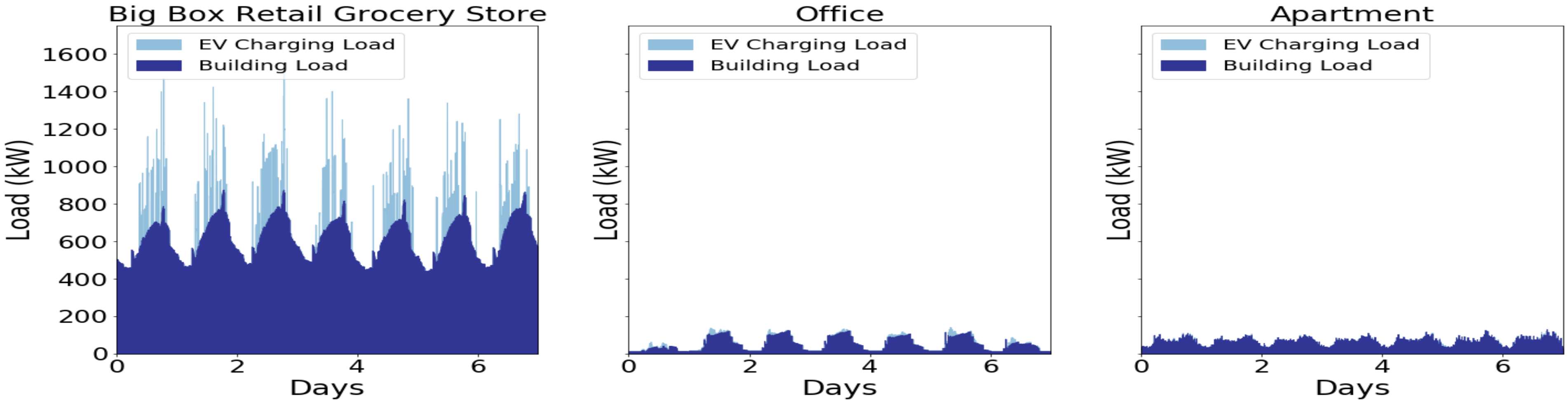
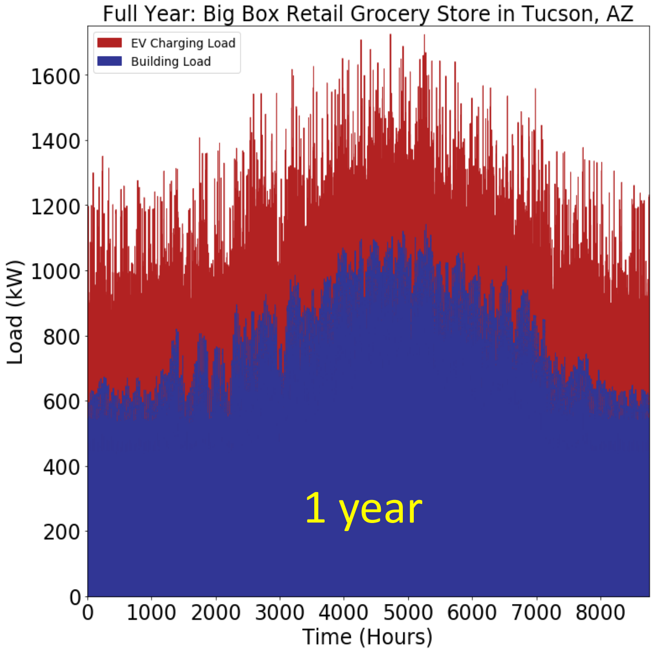
Combined Loads: Comparing Retail Big Box, Office & Apartment



Multiple use cases (building type, energy demand, location, climate, fast charging, EV-fleet, utility mix and rates etc) will define the needs for energy storage.

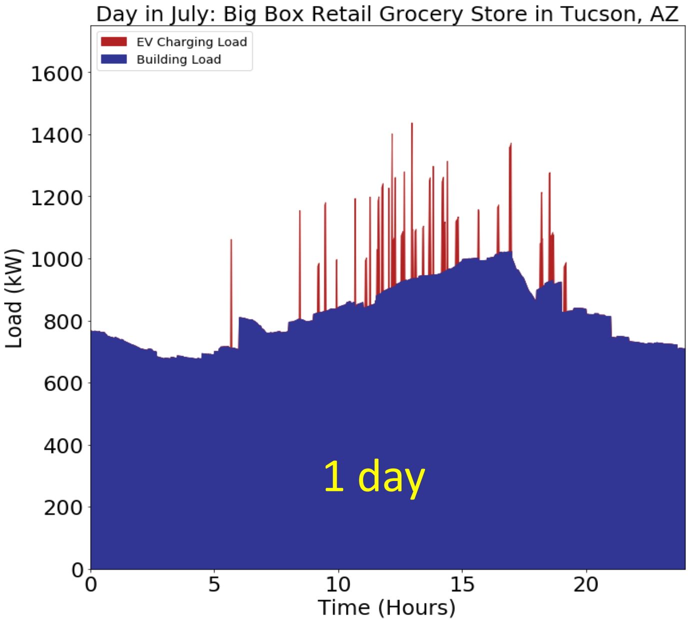
The big box retail + grocery building and electric vehicle station uses much more energy than the office or apartment building because the big-box + retail store is very large and has high loads (HVAC, refrigeration, lighting, etc.)

The Initial Use Case is Focused on Big Box Retail Grocery



The electric vehicle load profile is significant, with similar magnitude compared to that of the electric building load profile

A Big Box Store (BBS) that includes extreme fast charging is the 1st use case that will help define the requirements for energy storage in BTMS.



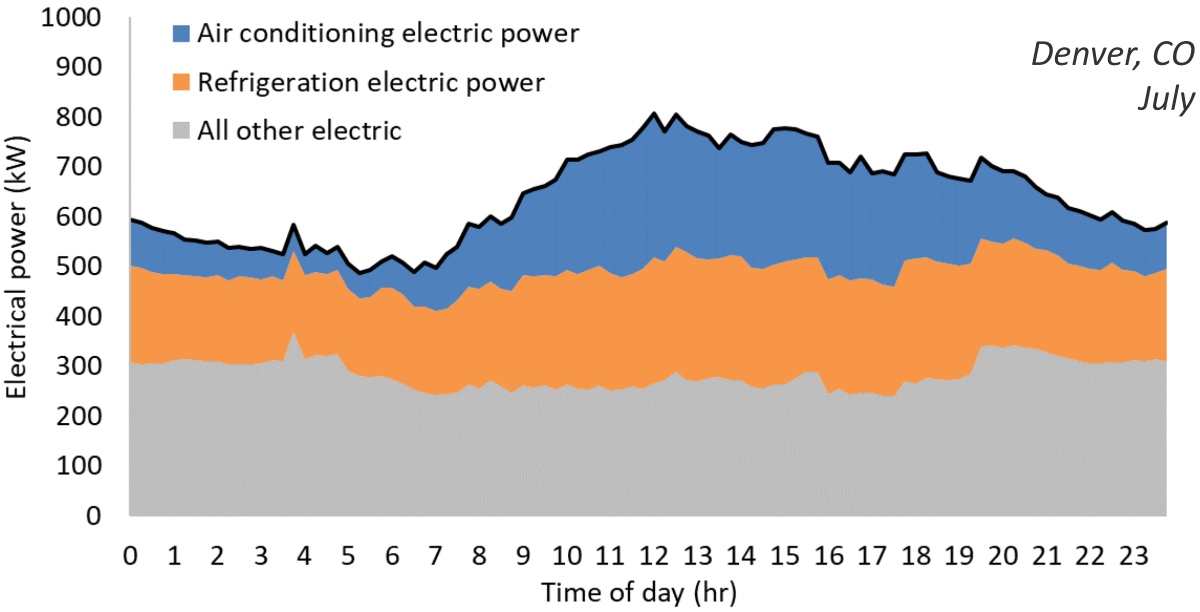
EV Assumptions:

Station Design: Two 350 kW ports

Station Utilization: 16 events per port per day

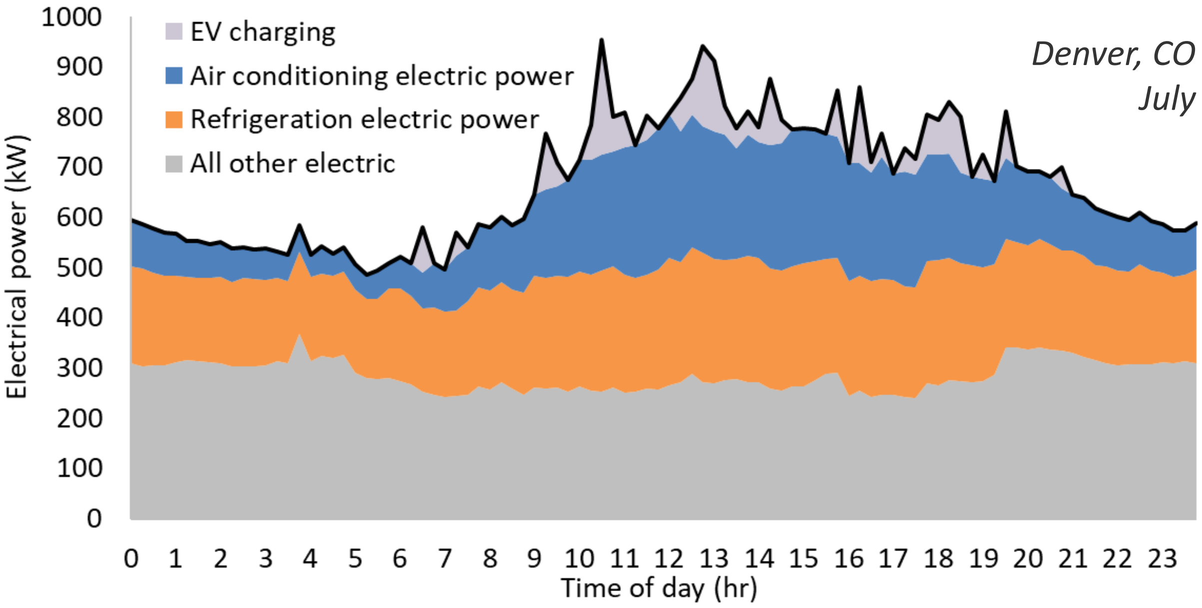
Why thermal storage?

Big-box grocery retail building load profile



Clearly much of the load in a BBS is associated with cooling. Time shifting this load may be more efficient (cost effective) using thermal storage.

Adding EV fast charging



However electrical energy storage will be likely be needed to deal with EV fast charging loads.

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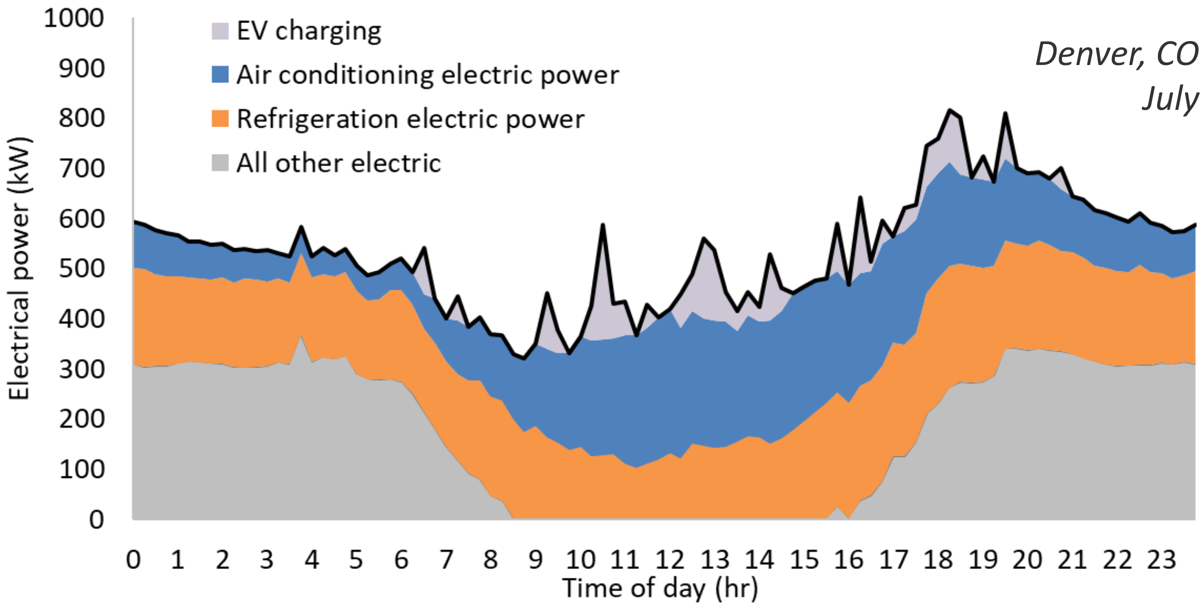
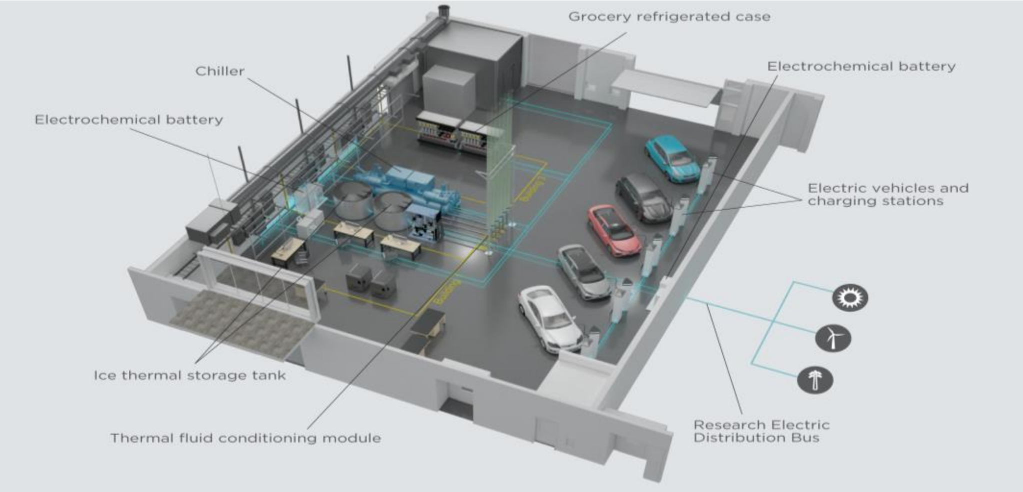
…adding PV to the mix



Behind the meter PV installations and a changing utility rate structure will impacts storage needs moving forward.

OCL: EV Charging, Commercial Buildings and BTMS Integration Laboratory



New Buildings/Vehicle lab established

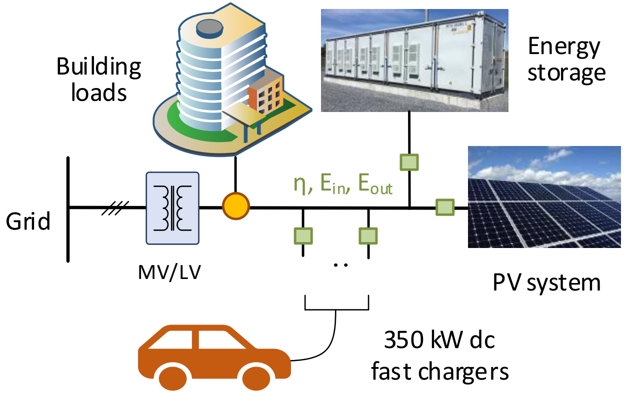
Battery storage systems

Vehicle and HIL charging stations

Thermal storage systems

Power System and Balance of Plant

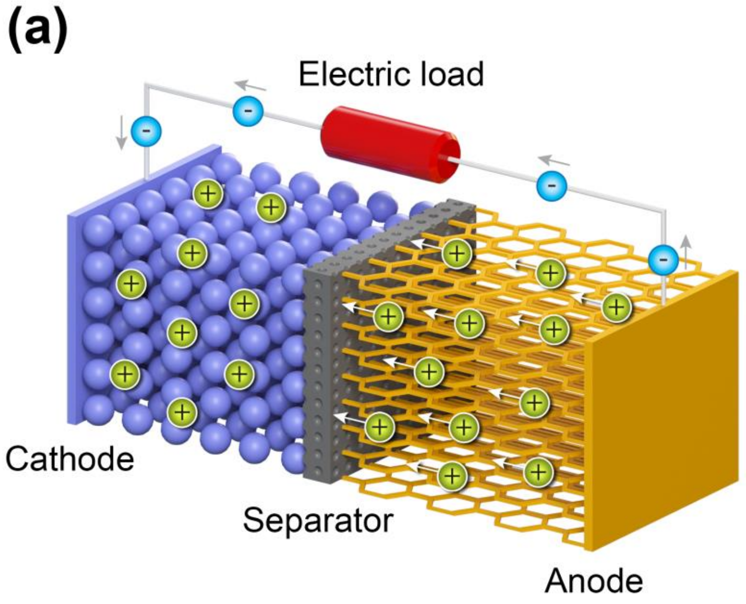
Energy Balance and Power Flow

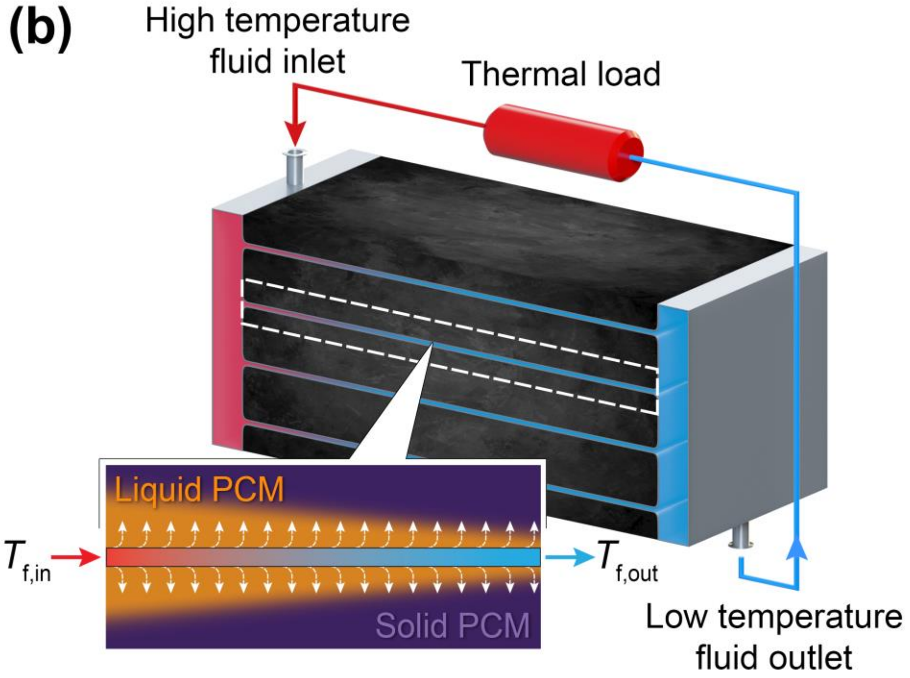


Power systems provide efficiency information for each energy conversion stage to the EnStore team. Advanced design options will be developed.

- The balance of plant, including the power conversion, is roughly 2/3 of the system cost in our technology targets.
  - Analysis from year 1 activities indicates a 50% reduction in these systems are required to meet our targets
- Support of EnStore analysis efforts to define and explore different potential system configurations for coupling ESS, PV system, building loads, and EV chargers, considering:
  - Conventional common AC bus
  - A common DC bus
  - Multiple bus
- Provide these configurations to the cost analysis team with the associated:
  - Efficiency data for each conversion stage.
  - Performance matrix, considering # of stage, size, reliability, maturity, control complexity, etc.
- Evaluation of battery management and cell balancing systems

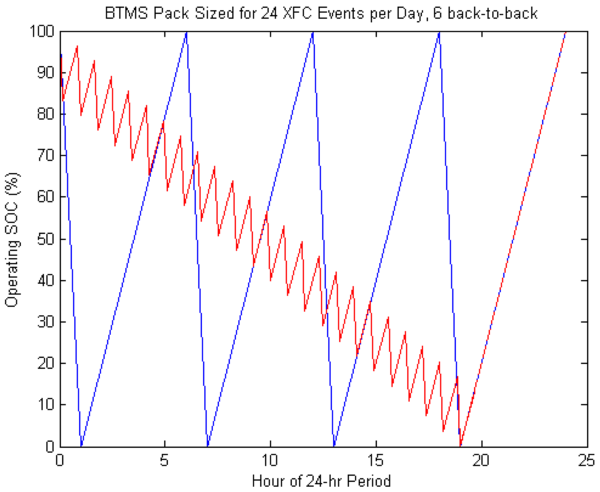
Materials: Analogy between battery and phase-change thermal energy storage





Storage options will depend on both the energy needs and the materials properties

Examples of 24-6 and 24-12



Device-level cycling protocol was developed to characterize BTMS system cells or modules, based on high level XFC station design criteria: number of 10-minute peak-power XFC sessions required 1) per day, and 2) between BTMS recharges.

Total energy use is the same but impacts on cells may be different. Lifetime impacts will be evaluated using testing and machine learning module

1 *XFC Duration (Minutes)*	*10*									
Peak-Day Station Design Parameters		**Max-Usage Results**					**Lifetime Implications**			
XFC Events per Day 2	Back-to-Back XFC Events 3	Total Discharge Hours per Day	Max BTMS Battery Cycles per Day	Discharge Time per Cycle	Max Charge Time per Cycle	BTMS Share of XFC Input Power (rough)	Minimum Years to 10,000 Cycles	Years to 10,000 Cycles if Avg usage = 0.5 Design Peak	Maximum Number of Cycles in 20 Years	Number of Cycles in 20 years if Avg usage = 0.5 Design Peak
24	6	4	4	1.0	5.0	0.83	6.8	13.7	29,200	14,600
24	12	4	2	2.0	10.0	0.83	13.7	27.4	14,600	7,300

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Ongoing and Upcoming BTMS Cell Testing

- **NMC622/Graphite** cells were cycled to EOL using 2-hr constant-current rates
  - Lifetime energy throughput was extended by 33% using a shallow, mid-50% SOC window
- **NMC/LTO** cells were cycled to ~5000 cycles with less than 2% capacity fade measured at the 2-hr rate, across various rate conditions
  - These cells continue to cycle, and indicate they may have a life of tens of thousands of cycles
- **LMO/LTO** cells are being placed on test as a benchmark and to evaluate the cycle life test developed, along with an extended test matrix to support ML activities.
- **Ni-Zn** cells were procured and will also be tested as a benchmark and to evaluate the cycle life protocol.
- **Pb Acid** systems begin evaluation in the next quarter.
- **Graphite/LFP** multiple cells being evaluated.
- **Zn-Air** looking to obtain test articles.

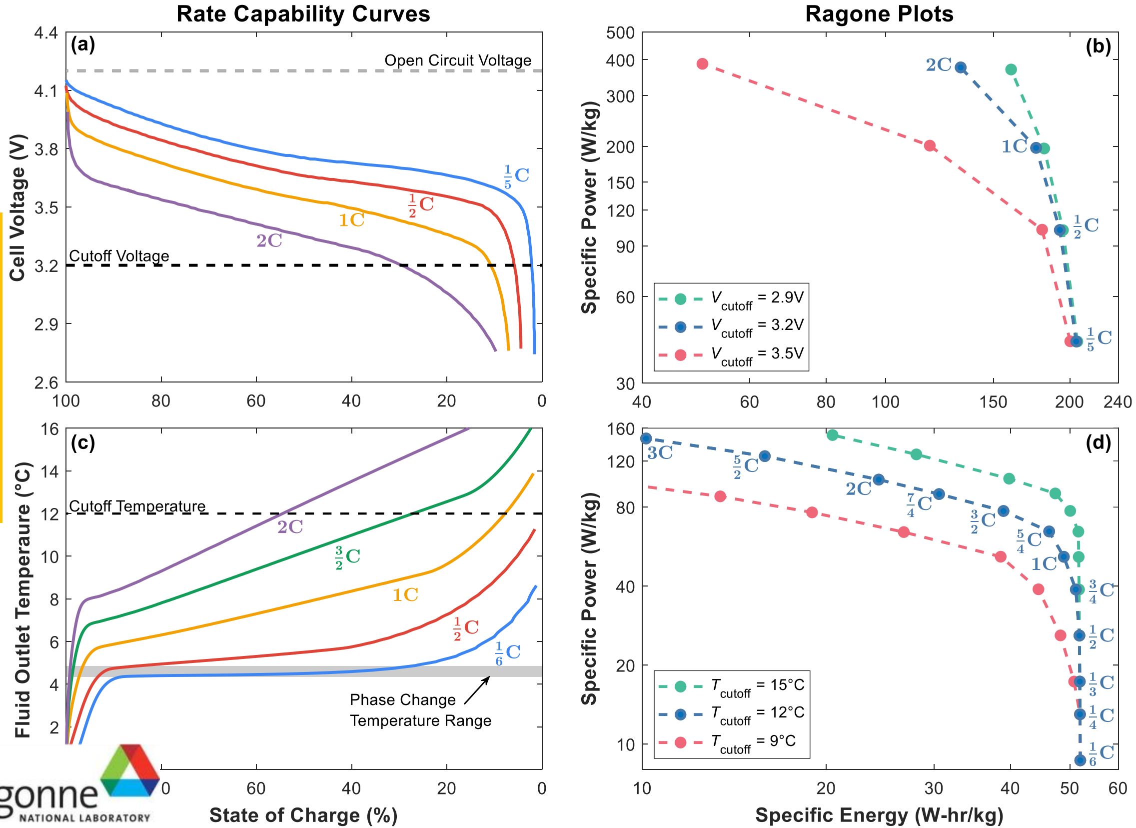
Ongoing effort to identify energy storage options research agendas that would enable BTMS.

Rate capability and Ragone plots for thermal storage

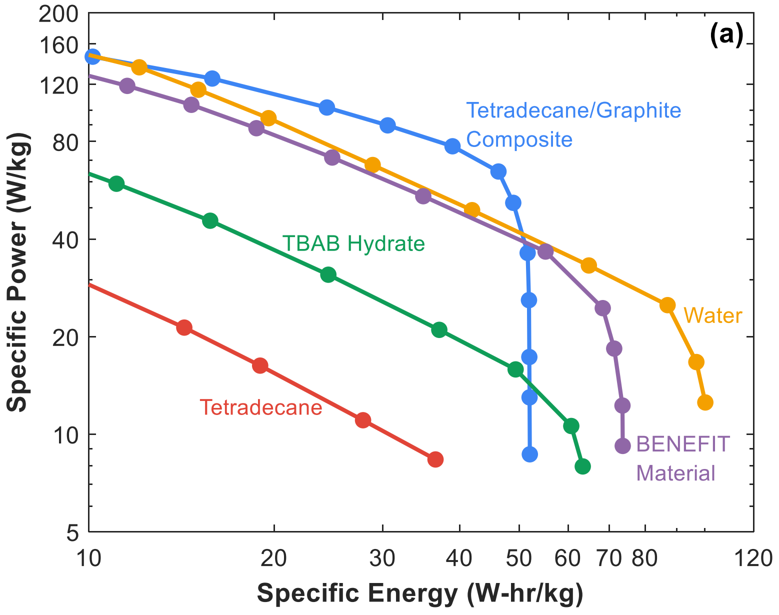
Electrochemical battery

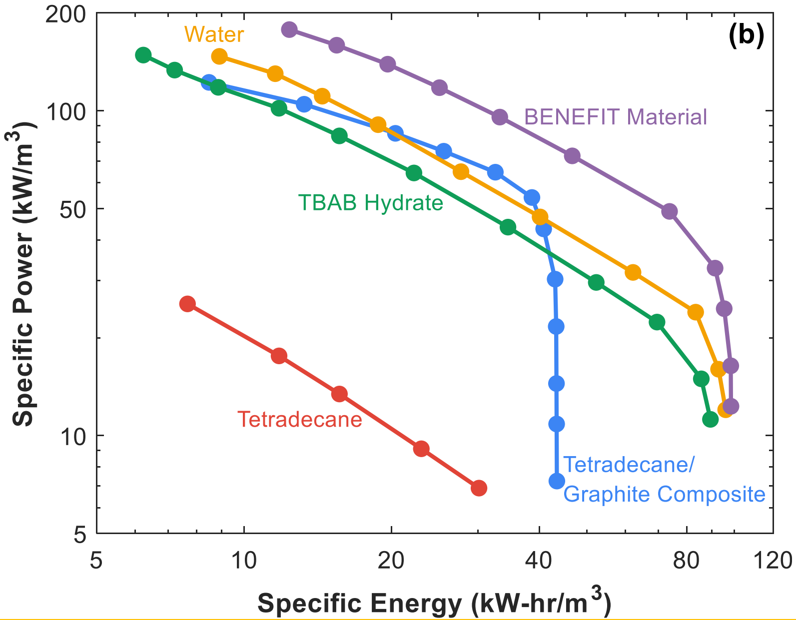
Defining the energy power capabilities for thermal storage materials will enable comparisons and down selects.

Phase-change thermal battery (cooling application)



This provides a new comparison framework for thermal storage materials and devices

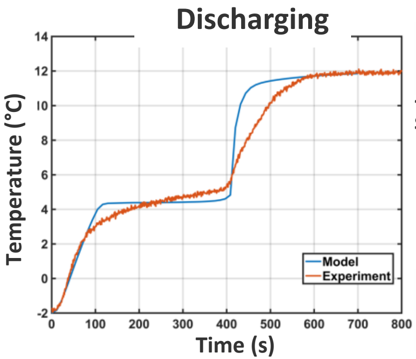


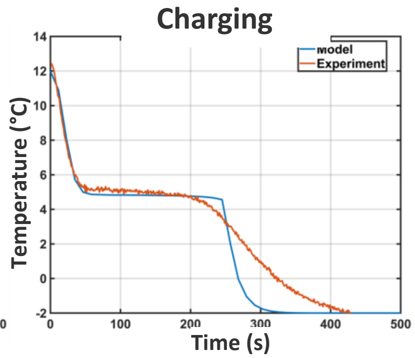


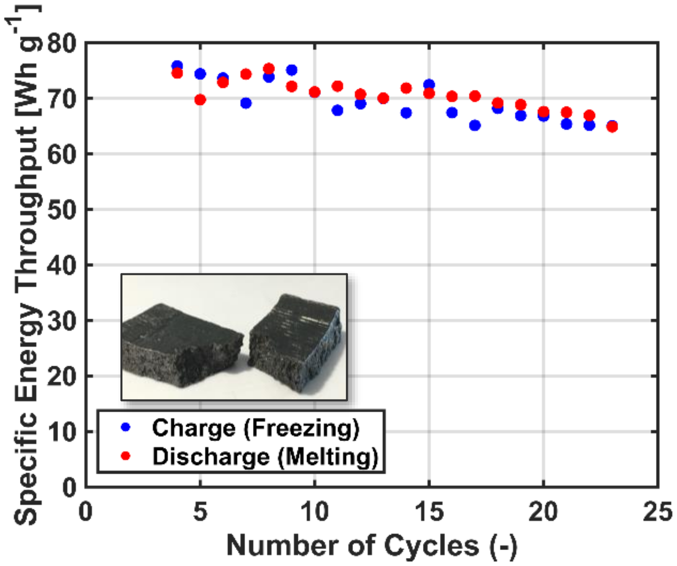
Data collected will enable device design, development and enhance the EnStore analysis

Thermal cycling experiments of phase-change materials

- Measure degradation in phase-change material energy capacity over time.







Lifetime information will be a critical metric for EnStore

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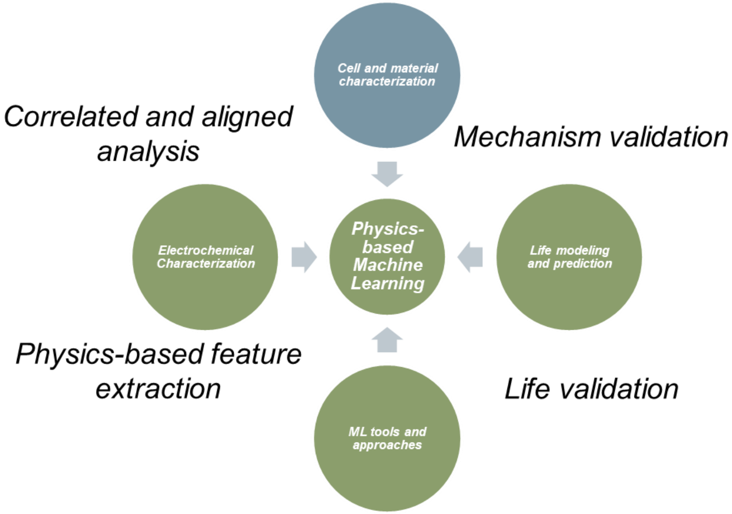
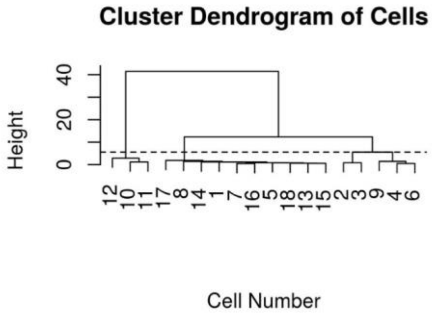
Physics-based Machine Learning – Understanding fade and life prediction

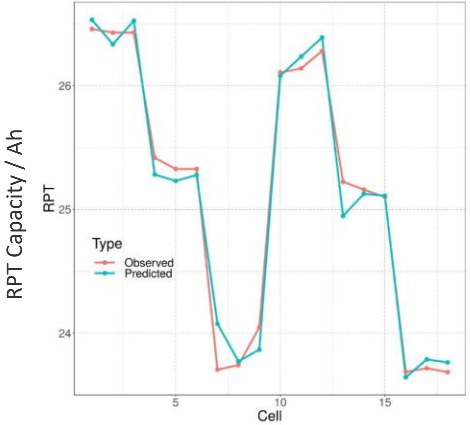
Using existing data from Nissan Leaf to define performance and mechanisms related to fade



Clustering similar fade for different cells undergoing variable aging profiles, identifying outlier data



Predicting performance using first 96 cycles to less than 1.5% mean error



Predicting battery life and performance over 20 years with fidelity, given major variations in use case, requires significant science.

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T. Tanim et. al, J. Power Sources ***2018****, 381, 56*

BTMS Materials Development

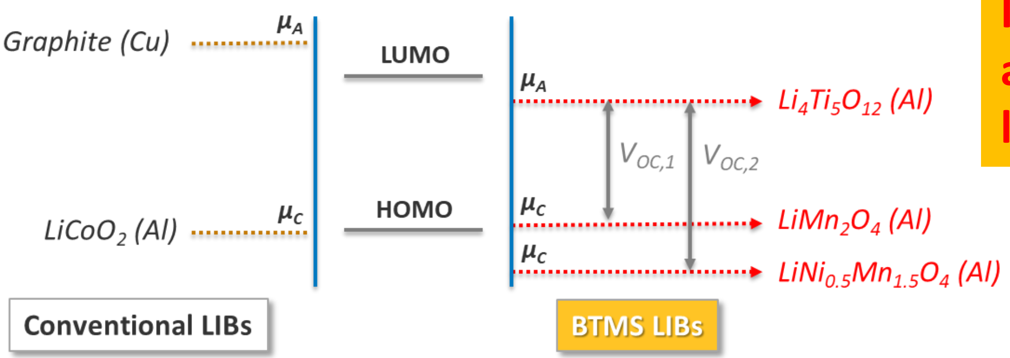
BTMS battery chemistry

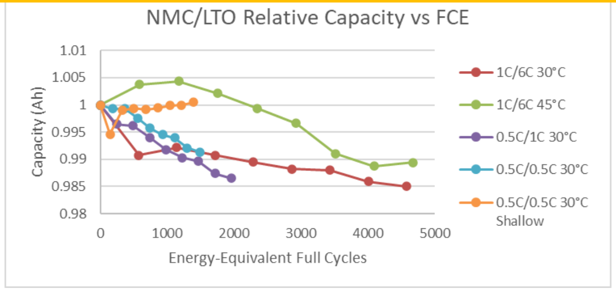
- Non-critical materials will be a foundation.
- **System safety is critical in a building environment.**
- Current targets for vehicles will not lead to batteries that meet long-term storage requirements.

✓ *Initial target chemistries*: **LTO/LMO & LTO/LMNO**

✓ *Key differences vs. conventional LIBs* : Working voltage window and operating temp.

Initial testing screen (FY19) identified LTO and LFP cells as the most likely to meet lifetime targets





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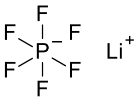
Electrolyte screening to find BTMS Gen1 electrolyte

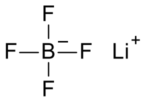
BTMS electrolyte chemistry

- LTO doesn't require good SEI forming additives, and LMNO needs a high voltage stability.
- Reducing cost of the electrolyte should be also considered.
- *Methods*: Electrochemical stability window tests (Al corrosion test), Half/Full cell tests

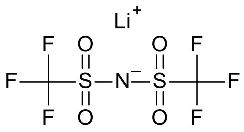
<u>Salt Candidates</u>



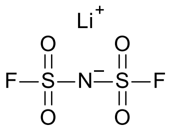
$LiPF_6$



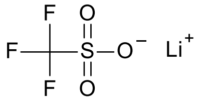
$LiBF_4$



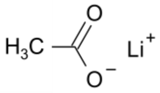
LiTFSI



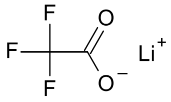
LiFSI



LiTf

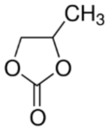


LiOAc

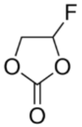


LiOTFAc

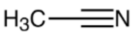
<u>Solvent Candidates</u>



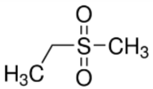
PC



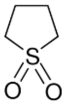
FEC



ACN



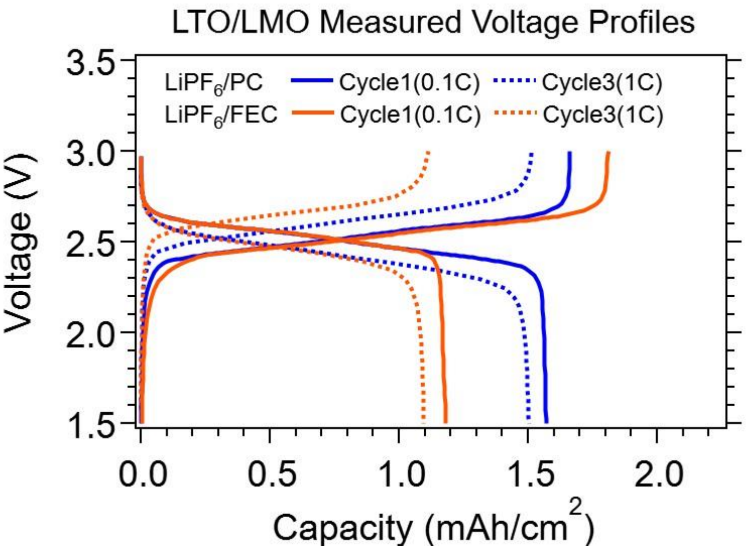
EMS



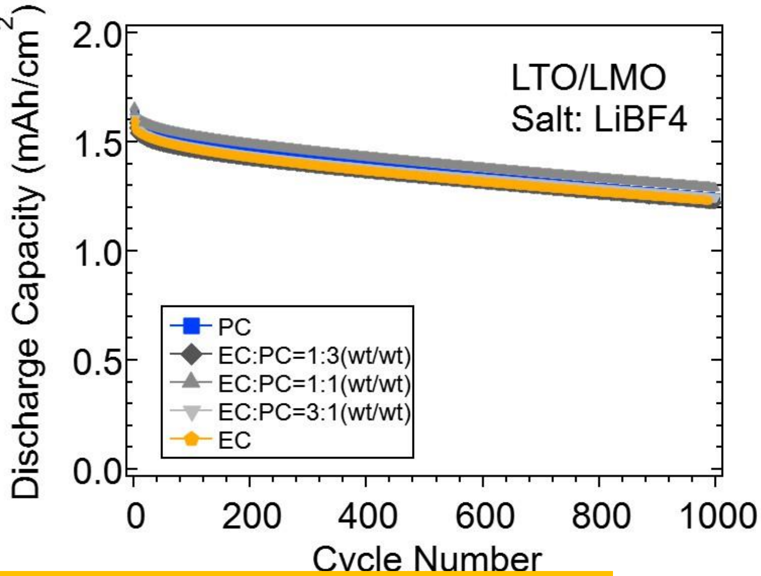
TMS

The BTMS requirements enable a wider range of possible electrolytes.

Example LTO/LMO full cells



Cheaper salts and less flammable electrolytes are available.



Not only cell chemistry but cell design are more flexible:

- **Thicker electrodes**
- **Higher temperatures**
- **Larger cells**

The Science of Safety

The potential safety risks of large-scale energy storage within buildings must be addressed by the BTMS design.

Need to address:

- No cell to cell propagation in potential thermal runaway.
- Requirement for reducing the combustible load at the storage level.
- Design for repair/maintenance and end of life.

These must be balanced against cost metrics.

BTMS will have a much higher emphasis on total design for safety moving forward.

Conclusions

Continual feedback from EnStore to/from the experimental team is critical for progress.

The best outcome will rely on a technologically agnostic solution to stationary storage that is guided by a system level assessment.

Non-critical materials must be a foundational issue if costs are to be controlled.

Safety of the energy storage solution will be a key outcome.

Thermal storage and management will enable optimizing energy efficiency and minimizing cost in buildings applications.

Advanced lifetime models will be necessary for long lifetime outcomes.

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NREL Transforming ENERGY

OCL: EV Charging, Commercial Buildings and BTMS Integration Laboratory

- Electric Vehicle Grid Integration
  - 2x individual sites, with each site including a 480-V and 208/120-V or 240/120-V systems
  - 2x extreme fast-charging systems with vehicles capable of 350-kW charging
  - Hardware-in-the-loop-integrated (HIL) control to enable experiments for DC charging of EVs
- Commercial Building Integration
  - Emulation of a building's thermal and electric loads for a specific climate that includes the chiller plant and thermal energy storage
  - Hardware-in-the-loop integration experiments to measure the performance of an ecosystem while representing some components in simulation
- Two 30KW/40kWh BTMS systems and of emulated PV first installed on buildings side and to be installed on transportation side

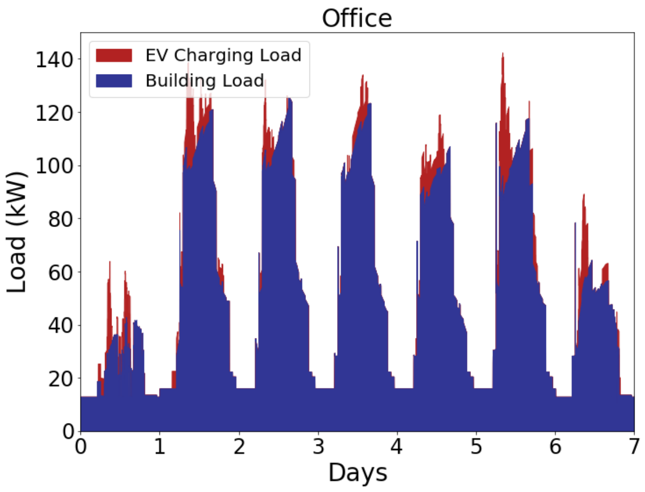
Battery storage systems

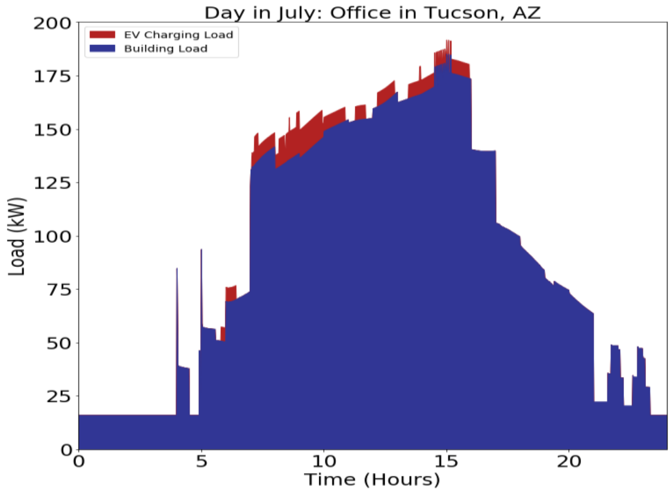
Vehicle and HIL charging stations

Thermal storage systems

Medium-Size Commercial Office: Building Loads

The DOE medium office prototype model (ran in Tucson, Arizona) was used to represent a typical medium-sized office building





EnStore Tools: More Details

- **REopt:** REopt uses a mixed-integer linear programming (MILP) approach to recommend the optimal mix of renewable energy, conventional generation, and energy storage technologies to meet cost savings, resilience, and energy performance goals. This MILP approach requires simplified, linearized models
- **EnergyPlus:** EnergyPlus is a whole-building energy simulation engine that engineers, architects, and researchers use to model both energy consumption and water use in buildings
- **OpenStudio:** OpenStudio is a suite of complementary tools that can expand EnergyPlus capabilities
- **SAM:** the System Advisor Model (SAM) is a techno-economic software model that can model many types of renewable energy systems, including photovoltaic systems, battery storage, concentrating solar power, and wind power

Multi-Model Optimization Approach

EnStore Main Model will use REOPT API, SAM (via PySAM), and OpenStudio/EnergyPlus:

- **REOPT**
    - Features: simplified MILP models; idealized controls
    - EnStore Use: preliminary optimal PV and stationary battery sizes for each application
- **SAM/PySAM**
    - Features: physics-based generator and storage models
    - EnStore Use: detailed battery degradation models and cash flow outputs
- **OpenStudio/EnergyPlus**
    - Features: detailed modeling of building systems
    - EnStore Use: model building loads, thermal storage, and multi-asset controls

REopt Inputs/Outputs in EnStore

REopt

Input Category	Description
Location	Latitude and longitude (REopt uses these to determine solar generation)
Electric Utility Rate Tariff Information	URDB label or custom rate tariff information
Cost Information	Solar PV installed cost per kW and O&M cost per kW; stationary battery installed cost per kW and installed cost per kWh; EVSE capital and O&M costs; interconnection cost
Detailed Component Information	Solar PV degradation percentage and existing kW; stationary battery replacement year, internal efficiency percentage, inverter efficiency percentage, inverter replacement year, max. kW, min. kW, initial SOC percentage, and min. SOC percentage
Load Profile	Aggregated building + EVSE load profile
Default Values	See REopt API documentation for details

Output Category	Description
Preliminary system sizes	Solar PV size (kW), stationary battery size (kW and kWh)

SAM Battery Model Inputs/Outputs in EnStore

Input Category	Description
Stationary Battery Characteristics	- Battery size (kW and kWh) - Battery chemistry - Battery performance curves (e.g. voltage vs. depth-of-discharge curve) - Battery control parameters (e.g. max./min. allowable SOC) - Battery replacement assumptions (e.g., replace when capacity drops to 80% of original capacity)
Default Values	See PySAM Battery documentation for details

Output Category	Description
Time-series Data	Various time-series data will be used for post-processing, including the following: - Battery SOC - Battery kW charging/discharging rates - Battery temperature - Battery capacity fade

EnergyPlus Inputs in EnStore

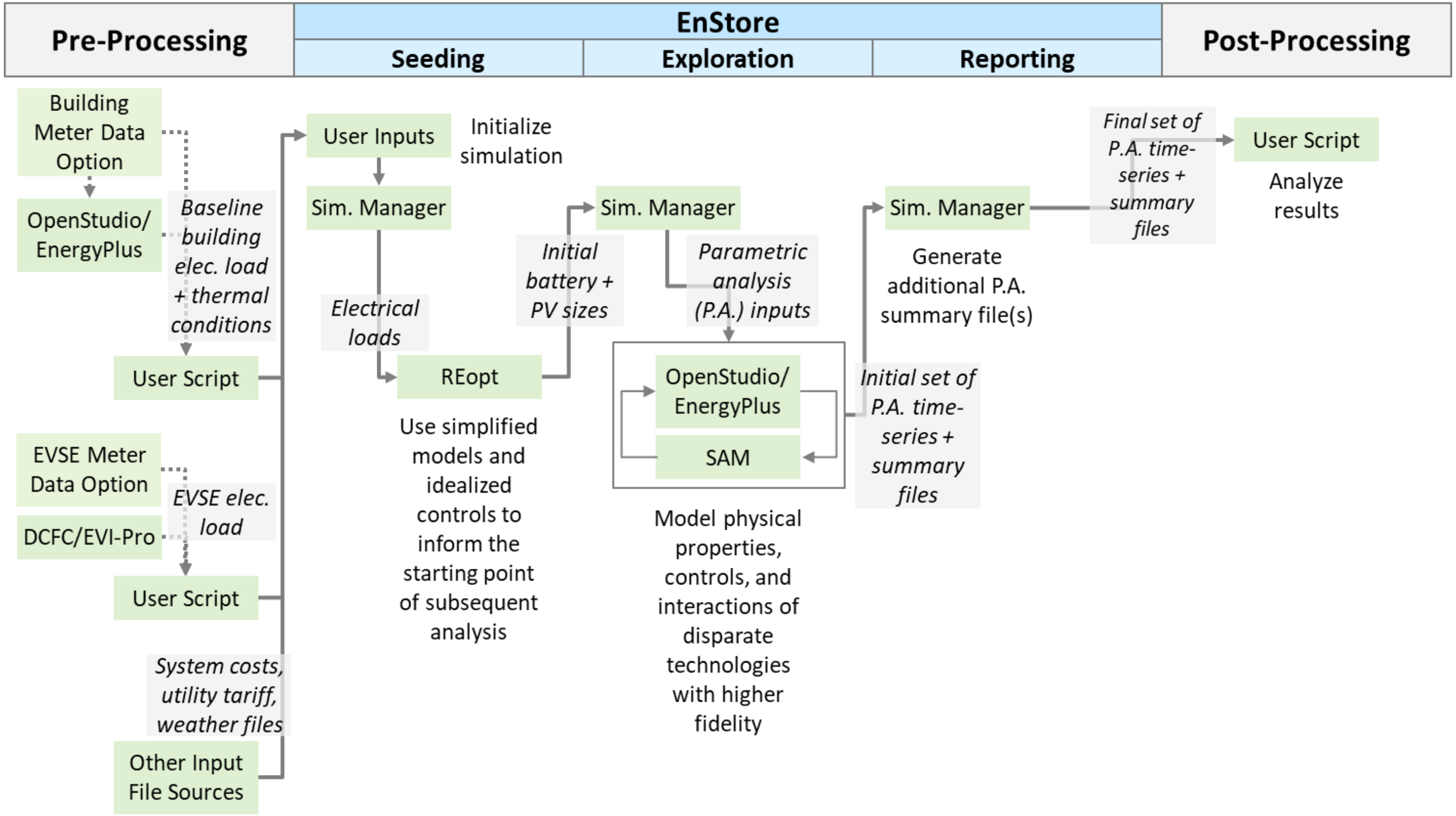
Input Category	Description
Baseline Building Model	Baseline building model (.idf or .osm file) with no solar PV, stationary battery, or TES. A different baseline building model will be created for each of the building types included in this project (retail big-box grocery store, commercial office building, fleet vehicle depot and operations facility, multi-family residential, and EV charging station)
Weather Data	Standard EnergyPlus format (.epw file)
Measures	In this context, “measures” are scripts for modifying building models in a replicable manner. EnStore inputs will include measures to add solar PV, stationary battery, and TES systems of various sizes.
Content for Python EMS	Depending on the application, examples may include: supervisory control logic for dispatching multiple energy storage systems; custom component models for novel TES technologies that differ from native EnergyPlus TES options; code for generating custom output variables.
Default Values	See the EnergyPlus Input Output Reference document for details

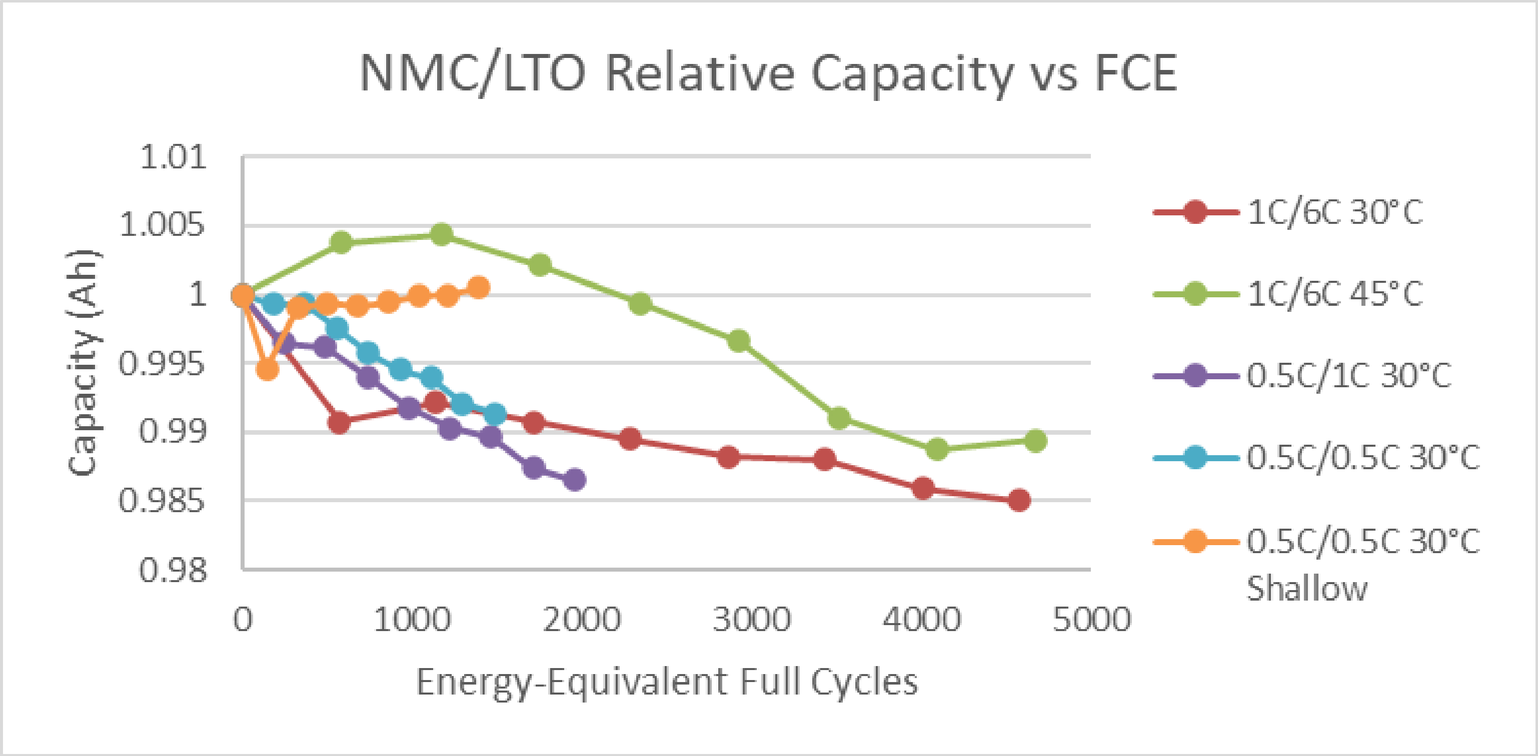
EnergyPlus Outputs in EnStore

Output Category	Description

Time-series Data	Various time-series data will be used for post-processing, including the following:
	- Electrical power from:
	  ○ Grid to stationary battery
	  ○ Grid to EV charging station
	  ○ Grid to building
	  ○ Solar PV to grid (if applicable)
	  ○ Solar PV to building
	  ○ Solar PV to EV charging station
	  ○ Stationary battery to building
	  ○ Stationary battery to EV charging station
	  ○ Stationary battery to grid (if applicable)
	- Electrical input to TES systems
	- Thermal input to TES systems
	- Thermal output from TES systems
	- System losses
	- Other system and subsystem loads and conditions

EnStore Flow Diagram





NMC/LTO Relative Capacity vs FCE
1.01
1.005
1
0.995
0.99
0.985
0.98
Capacity (Ah)
0
1000
2000
3000
4000
5000
Energy-Equivalent Full Cycles
1C/6C 30°C
1C/6C 45°C
0.5C/1C 30°C
0.5C/0.5C 30°C
0.5C/0.5C 30°C Shallow